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Manufacturing Technology Information Analysis Center

MTIAC SOAR-88-01

AUTOMATED INSPECTION FOR FLEXIBLE MACHINING SYSTEMS

May 1988

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Cresap, a Towers Perrin Company

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Under Contract to the
Department of Defense
Contract Number DLA900-84-C-1508

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A Department of Defense Information Analysis Center

Overview

MTIAC is a Department of Defense (DoD) Information Analysis Center. MTIAC serves as a central source for currently available and readily usable data and information concerning manufacturing technology. The primary focus of the Center is to collect, analyze, and disseminate manufacturing technology for the production of defense materials and systems.

The funding agency for MTIAC is the Defense Technical Information Center of the Defense Logistics Agency of the Department of Defense, in Alexandria, Virginia. MTIAC's data collection and dissemination function is tied to DTIC by a shared bibliographic data base.

The DoD supports manufacturing technology programs conducted by the Air Force, Navy, and Army as well as by the Defense Logistics Agency. MTIAC's role is to support the effective use of manufacturing technology by DoD agencies and the industrial contractor base, at both the prime contract and subcontract level. This support is provided through a range of services from technical inquiries to bibliographic searches and special tasks within the scope of the contract. Services are offered on a fee-for-service basis to subscribers and nonsubscribers.

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Activities Scope

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- Maintains a DoD Manufacturing Technology Program (MTP) data base
- Prepares and publishes handbooks, data books, reference works, state-of-the-art reviews (SOARs), critical reviews and technology assessments, conference proceedings, newsletters, and other publications
- Responds to technical, bibliographic, and other user inquiries
- Establishes and maintains programs of awareness and visibility of MTIAC capabilities and services to promote the Center's use
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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

ADA198231

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE			Unlimited		
4. PERFORMING ORGANIZATION REPORT NUMBER(S) MTIAC SOAR-88-01			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Cresap, McCormick & Paget Division of TPF&C Inc.		6b. OFFICE SYMBOL (If applicable)		7a. NAME OF MONITORING ORGANIZATION Dr. Lloyd Lehn Production and Logistics (PS/IR)	
6c. ADDRESS (City, State, and ZIP Code) 200 West Madison Chicago, IL 60606		7b. ADDRESS (City, State, and ZIP Code) Office of the Asst. Secretary of Defense Pentagon, Room 3C257 Washington, DC 20301-8000			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Defense Logistics Agency		8b. OFFICE SYMBOL (If applicable) DTIC-DF		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DLA 900-84-C-1508	
8c. ADDRESS (City, State, and ZIP Code) Cameron Station Alexandria, VA 22304-6145		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO.		PROJECT NO.	TASK NO.
					WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) AUTOMATED INSPECTION FOR FLEXIBLE MACHINING SYSTEMS					
12. PERSONAL AUTHOR(S) Edward J. Maksym, Jr.					
13a. TYPE OF REPORT SOAR		13b. TIME COVERED FROM TO		14. DATE OF REPORT (Year, Month, Day) May 1988	
15. PAGE COUNT 45					
16. SUPPLEMENTARY NOTATION This state of the art review is available only through MTIAC. Reproduction is not authorized except by specific written permission.					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	flexible machining systems, (FMS)		
			automated inspection		
			post-process inspection (continued on reverse)		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Automated inspection is a broad classification of techniques which can, without the aid of human intervention or interpretation, determine whether or not a manufactured part or manufacturing process has characteristics which meet predetermined limits or criteria. These criteria can be shape, weight, size, hardness, or surface finish to name a few. Recent improvements in electronic sensing, instrumentation, vision signal and image processing, data logging, software, and computer control of machining operations have expanded the opportunities for expanding the use of automated inspection in flexible machining systems. These improvements in technology allow substantial improvements in the accuracy, speed, and repeatability of inspection measurements. Improved inspection operations improve quality, reduce lead time, and reduce product cost. (continued on reverse)					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Robert A. Walk			22b. TELEPHONE (Include Area Code) (312) 263-7125		22c. OFFICE SYMBOL

18. SUBJECT TERMS (continued)

on machine gaging,
deterministic metrology,
independent inspection,
coordinate measuring machine, (CMM)
dimensional measurement interface specification, (DMIS)

flexible inspection system, (FIS)

sensors

Automated Manufacturing Research Facility (AMRF)

19. ABSTRACT (continued)

The scope of this review of automated inspection is the application of automated inspection to flexible machining systems. Examples of the application of automated inspection are presented in the review. The review also discusses the enabling technologies such as sensors, vision systems, process control, and computer software. Several conclusions about the state of the art in automated inspection for flexible machining systems are discussed along with recommendations for developing and planning new applications of automated inspection within flexible machining systems.

THE MANUFACTURING TECHNOLOGY INFORMATION ANALYSIS CENTER (MTIAC)

The objective of MTIAC is to support the Department of Defense in achieving an improvement of the productivity and responsiveness of the defense industrial base. This support is to be provided chiefly through the collection, analysis, and dissemination of timely manufacturing technology information and the provision of technical services. The dissemination to the MTIAC customer base is through support to inquiries and the development of products.

The Center concerns itself with areas of manufacturing technology that are applicable to defense systems. These areas include but are not limited to: metals, nonmetals, electronics, CAD/CAM, inspection and test, and munitions. The term "manufacturing" covers the entire lifecycle of a product, i.e., design, production, and operational support.

Each of the above six subject areas includes but is not limited to the defense-related fields of: machine tools and manufacturing equipment, robots and special machines, material handling equipment, controls, software and data bases, communication lines and networks, sensors and inspection or checkout procedures, signal processing, materials and materials treatments, production processes, the specific defense products being produced, and management aspects of manufacturing technology.

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DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By MTIAC-50.00 <i>see inside front cover</i>	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-121	



PREFACE

This state of the art review was prepared by the Manufacturing Technology Information Analysis Center (MTIAC) under Contract DLA 900-84-C-1508 for the Department of Defense.

It reviews the use of automated inspection in flexible machining systems. This review is intended as a primer on automated inspection for flexible machining systems and as an initial source of information for managers, manufacturing engineers, and system designers who are beginning to research the feasibility of including automated inspection in their planning for a flexible machining system.

The discussion, examples, and conclusions presented in the review are derived from on-site visits and telephone interviews with users and vendors of equipment, researchers in areas of enabling technologies, and authors of books and articles related to the scope of the topic. The subject terms listed in block 18 of the report documentation page were used to identify published literature on the topic. The available literature was reviewed and is included as reference documentation and material where appropriate.

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EXECUTIVE SUMMARY

The objective of this review is to define the state-of-the-art of automated inspection for flexible machining systems. This review is intended as a primer and as an initial source of information for managers, manufacturing engineers, and system designers who are beginning to research the feasibility of including automated inspection in their planning for a flexible machining system.

There are numerous applications of automated inspection that are being used in many areas of manufacturing such as assembly, machining fabrication, and quality control of material processes. The scope of this paper is limited to the use of automated inspection in flexible machining systems. There are several definitions of flexible machining systems. This paper considers an FMS to include at least two machine tools that can change the shape or features of a machined part. These machine tools are linked together by a material handling device and are controlled by a computer.

Most of the automated inspection approaches and technologies used for flexible manufacturing systems are also being used in single-machine or stand alone installations. The major difference is that FMSs require significantly more integration of data between sensors, process control computers, and system host computers.

The development and implementation of flexible machining systems (FMS) is changing the rules for inspection and quality control. In traditional manufacturing operations, a part is inspected after a machining operation and is either accepted, reworked, or scrapped. The inspection step is often performed hours or even days after the machining step is completed. Sampling inspection techniques are used for parts produced in large lot sizes. Depending upon the nature of the part and the stability of the processes used, these techniques virtually ensure the manufacture of defective parts.

There are several approaches for integrating the inspection steps into an FMS. These approaches to integrating inspection have variations in inspection philosophies, hardware, software, data requirements, data communications, sensing devices, and levels of automation. The advantages and disadvantages of the integration approaches tend to be application-specific. That is, what may be an advantage in one application is a disadvantage in another application.

Four key conclusions can be made based on the information available about automated inspection in flexible machining systems.

1. There are very few FMS installations that have automated inspection fully integrated into the system.
2. A major factor is the reluctance of management to invest large amounts of capital because of concerns about the length of the payback period.
3. Many vendors, user groups, and research institutions are actively involved in research and development in all aspects of automated inspection.
4. The trend in FMS automated inspection is toward controlling the process through in-process gaging and deterministic metrology.

Development in inspection technologies, sensors, systems control software, and communications software are facilitating the integration of automated inspection into flexible machining systems. These developments are also improving the practicality and economics of FMSs. The range of inspection methodology alternatives available to designers and planners of flexible manufacturing systems is also increasing. Because of the many alternatives and variables involved in integrating automated inspection into an FMS, it is not realistic to make specific recommendations. Each potential application must be analyzed to determine the configuration that will optimize the manufacturing system and not just the inspection operation. Analysis of an opportunity to integrate automated inspection into an FMS should include the six steps listed on page 46 of the review.

Integration of automated inspection methods and equipment that are appropriate for the product and the process does not add to the life-cycle costs of a flexible machining system. The resulting improvements in productivity and quality and the reductions in inventory, scrap, and rework costs all improve the profitability of the system.

The examples of automated inspection in flexible machining systems cited in this review demonstrate that the technology is working. Companies are getting benefits from integrating automated inspection into their FMSs. Why wait for developments that may only add ten to twenty per cent to the benefits that are already available? Managers at all levels need to aggressively pursue opportunities to use this technology to reduce product costs and to improve productivity, quality, and market share.

1.0 INTRODUCTION

1.1 AUTOMATED INSPECTION

The development and implementation of flexible machining systems (FMS) is changing the rules for inspection and quality control. In traditional manufacturing operations, a part is inspected after a machining operation and is either accepted, reworked, or scrapped. The inspection step is often performed hours or even days after the machining step is completed. Sampling inspection techniques are used for parts produced in large lot sizes. Depending upon the nature of the part and the stability of the processes used, these techniques virtually ensure the manufacture of defective parts.

Flexible machining systems allow the inspection steps to be integrated into the machining process. In fact, the inspection steps must be integrated into the process to achieve the maximum benefits of an FMS which include:

- operating flexibility
- consistent part quality
- elimination of learning costs on low volume production
- reduction of set-up costs
- untended operation which reduces manpower costs and increases utilization by adding extra work shift capacity.

There are several approaches for integrating the inspection steps into an FMS. These approaches to integrating inspection have variations in inspection philosophies, hardware, software, data requirements, data communications, sensing devices, and levels of automation. The advantages and disadvantages of the integration approaches tend to be application-specific. That is, what may be an advantage in one application is a disadvantage in another application.

As an example, integrating an inspection step into the machining sequence while a part is still located in the fixture in the machine may be an advantage in producing a single part that has critical tolerance requirements. This same inspection integration technique may be a disadvantage to producing several parts in a capacity constrained FMS component station because of the added machine cycle time.

The factors that need to be considered when evaluating the advantages and disadvantages of a method of integrating inspection into an FMS include:

- marketing and manufacturing strategy
- part design
- material characteristics
- machining process
- applicable inspection technologies
- critical features and tolerances
- production volume
- organization
- capital resources.

This document presents a review of published literature and of several recent FMS installations to determine:

- how the inspection components have been integrated
- what inspection technologies are available to facilitate the integration
- what problems and difficulties were encountered
- what benefits were achieved from integrating the inspection steps into the FMS

The objective of this review is to define the state-of-the-art of automated inspection for flexible machining systems. This review is intended as a primer and as an initial source of information for managers, manufacturing engineers, and system designers who are beginning to research the feasibility of including automated inspection in their planning for a flexible machining system.

1.2 SCOPE

There are numerous applications of automated inspection that are being used in many areas of manufacturing such as assembly, machining, fabrication, and quality control of material processes. The scope of this paper is limited to the use of automated inspection in flexible machining systems. There are several definitions of flexible machining systems. This paper considers an FMS to include at least two machine tools that can change the shape or features of a machined part. These machine tools are linked together by a material handling device and are controlled by a computer.

Most of the automated inspection approaches and technologies used for flexible manufacturing systems are also being used in single-machine or stand alone installations. The major difference is that FMSs require significantly more integration of data between sensors, process control computers, and system host computers.

Research for this paper included a study of published literature and visits or telephone interviews with vendors and users of automated inspection equipment, flexible machining systems, and laboratories working on manufacturing technologies. The references cited in the text of this review are listed in Appendix A. Appendix B is a bibliography of the publications reviewed during the research for this document.

1.3 BACKGROUND

Flexible machining systems were first introduced during the middle 1960s. The early systems were designed primarily to reduce or eliminate direct labor from the machining process. Many system designers believed that automating the process and removing the direct labor variable from the process would reduce the need for inspection. Typically, inspection operations were not integrated into the machining process. Inspection continued to be on a sampling basis after value was added to the product by the machining operations.

Management groups are beginning to view manufacturing as a strategic resource that complements the business and marketing strategies of the business. As a result, design emphasis for current machining systems is on providing operating flexibility which permits manufacturing strategies such as:

- reductions in work-in-process and finished goods inventories
- defect free parts
- shorter lead times from order to delivery
- increased utilization of assets
- reductions in lot sizes.

These changes in manufacturing strategies, especially the need for defect-free parts, have changed inspection requirements from sampling inspection of batch-produced parts to 100 per cent inspection of individually produced parts. This change in inspection requirements is forcing the integration of inspection operations into the flexible machining systems.

There are four opportunities during the machining process to ensure that a defect-free part is being machined.[1.1] These opportunities are identified below and are described in detail in later sections of this review. Each of these process cycle opportunities can also be labeled as an inspection technique based on its position in the process cycle.

Traditionally, the part is inspected after one or more machining steps have been completed. Most efforts at automating the inspection steps have been directed at these post process inspection operations. Post process inspection is almost always performed in work stations that are separate from the machining operations but integrated into the FMS by material handling devices and control systems. Post process inspection in off-machine work stations is commonly referred to as independent inspection.

A variation of post process inspection occurs when the part is inspected after the machining step but while the part is still located in the fixture in the machine tool. Advancements in sensor technologies are making this form of post process inspection more reliable and accurate.

A third opportunity to inspect a part is during the machining process by using sensors to measure the dimensions and characteristics of the part. Currently, this technique is used in grinding operations more often than in cutting operations. This method of on-machine gaging during cutting operations is gaining acceptance as new sensing devices for non-contact measurement are developed that do not interfere with the cutting process.

The fourth opportunity to ensure a defect-free part is to inspect the process rather than the part. This technique is called deterministic metrology. It is based on the assumption that if the process parameters are correct then the part must be correct. Deterministic metrology monitors and adjusts the machining process to maintain the process within specified operating range. The concept has been used in process control industries such as petroleum refining for many years.

The advantages and disadvantages of the four techniques are summarized in Table I-1. These advantages and disadvantages need to be considered when designing an FMS.

TABLE I-1

ADVANTAGES AND DISADVANTAGES OF FOUR INSPECTION TECHNIQUES

Independent Inspection

Advantages

- no increase in machine cycle time
- independent of machine system errors
- use data to adjust process for next part
- accepted and proven technology

Disadvantages

- inspects part after value added
- identifies errors instead of preventing
- adds to system cycle to correct part

Post-process Inspection

Advantages

- maintains set-up in machines
- uses machine tool as inspection station
- possible to add machining ste to correct part while part is on machine

Disadvantages

- inspects part after value is added
- can be affected by machine system errors
- adds to machine cycle time
- difficult to adjust for fixture-caused distortion
- technology is available but less proven

On-machine Gaging

Advantages

- adjust process to compensate for machine system errors
- optimizes cutting cycle
- inspects part during machining cycle

Disadvantages

- limited by sensor reliability and accuracy
- all surfaces not accessible
- technology is less advanced

Deterministic Metrology

Advantages

- reduces need for separate inspection step
- no addition to or interference with machines cycle time
- ensures defect-free parts

Disadvantages

- limited by sensor reliability and accuracy
- need to create model of good process
- technology is in early stages of development

As will be seen in the following sections, these inspection alternatives are in various stages of development and application. The automation of independent inspection stations is well established as a technology. The acceptance of the other three approaches is tied to the development of sensors that can exist in harsh environments and continue to function accurately and reliably.

A truly flexible system should be able to use a combination of these approaches in order to select an appropriate inspection technique for the job. A combination of deterministic metrology and independent inspection stations may be very desirable in situations where it is necessary to frequently qualify the machining process. This combination would use the independent workstation to periodically verify the accuracy of the machining process. The data accumulated by the inspection station would be used to verify the accuracy of the deterministic metrology systems, identify opportunities for improvement, and provide documentation of the manufacturing process.

The actual integration of the inspection operation into an FMS requires a hierarchy of control systems. The control systems are used by the host computer for a variety of tasks such as data storage and transfer, process control and monitoring, scheduling, record keeping, and reporting system status or performance. Control systems are discussed in Section 6.0 of this review.

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2.0 INDEPENDENT INSPECTION

Independent inspection uses a separate workstation within the flexible machining system to measure the features of the workpiece and compare the collected data to part information contained in the part description file in the data base. The part is accepted or rejected based upon the calculated difference between the observed part and the stored model. Inspection data can also be used to adjust the process and to track the production trends.

2.1 COORDINATE MEASURING MACHINES

Automating an independent inspection station requires a system for locating the inspection points on a part in relation to a known reference point. Coordinate measuring machines (CMM) have become the accepted technology for independent inspection stations. CMMs have been used for many years in different industries. The computerized versions that have been developed more recently have been integrated into flexible machining systems. Their computerized controls allow them to be treated as any other Computer Numerically Controlled (CNC) machine in the system. Some unique requirements in the control systems are needed because the part description data used by a CMM is different than the data needed to control a CNC machine. These differences are discussed in Section 6.2, part definition, later in this review.

Several examples of automated independent inspection stations that are part of FMS operations are described in the next section. They represent installations of several of the leading CMMs. These CMMs are manufactured by companies such as:

- Sheffield Instruments
- Brown & Sharpe
- L-K Industries
- Mauser
- Digital Electronics Automation (DEA)
- Zeiss

Table II-1 shows a comparison of the characteristics of CMMs from four of these vendors. There is a wide range of models available which allows the customer to choose a CMM size and accuracy that best fits the intended application. These vendors, and others, also provide interfaces to other systems such as CAD/CAM and material handling that permit integration into an FMS.

The ability of a CMM to communicate to other components of an FMS is key to the success of automating the inspection step. The development and growing acceptance of common languages and protocols (discussed in section 6.0) has been a major factor in the increasing integration of automated inspection in FMSs.

2.2 APPLICATION EXAMPLES

The following descriptions of current applications of automated independent inspection stations in flexible machining systems are based on site visits, telephone interviews, and published literature. They are systems that have been installed within the last two years or are in the planning process. There are also descriptions of three non-FMS installations that are relevant to this review because they demonstrate a level of integration that could be transferred to flexible machining systems.

2.2.1 LTV - Dallas

The Vought Aero Products Division of LTV Aerospace and Defense Co. manufactures airframe parts for a number of airplane manufacturers. They are installing an FMS to machine 4 sets of 541 parts each month to meet the requirements for one of their major contracts. The components of the FMS are:

Table II-1

COMPARISON OF CMM CHARACTERISTICS

Characteristics	CMM Vendors			
	L-K	Brown And Sharpe	Sheffield	DEA
Model Types				
Vertical Arm	-	-	X	-
Horizontal Arm	X	X	X	X
Double Horizontal Arm	X	X	X	X
Bridge/Gantry	X	-	X	X
Smallest	20"x20"x10"	19.7"x11.8"x11.8"	40"x30"x25"	26"x12"x12"
Largest	315"x120"x120"	39.4"x19.7"x27.6"	48"x80"x40"	235"x96"x78"
Interfaces				
CAD System	X	X	X	X
CAM/DNC	X	X	X	X
Material Handling	X	X	X	X
On-Line Programming	X	X	X	X
Off-Line Programming	X	X	X	X
Probe Change	X	X	X	X
Laser/Optical Probes	X	X	X	X
Error Compensation	X	X	X	X
Statistics Package	X	X	X	X
Reports System	X	X	X	X
Performance Data				
Positioning Speed		20"/Sec	10"/Sec	1,300"/Min
Volumetric Accuracy		+0.0004/+0.001	+0.0005	N/A
Resolution		0.001	0.00004	0.0001
Rotary Index Table		+5 ARC Sec	-	-

- Eight single spindle machining centers with tool changers
- Three 10-station carousels for part queuing, part loading and unloading
- Four wire-guided automatic guided vehicle carriers to transport parts between work stations
- An automatic cleaning station
- Two Digital Electronics Automation 4-axis coordinate measuring machines with positional accuracy to 0.0005 inches

This FMS configuration (Figure 2.1) is the result of several computer simulations to compare the performance of various material handling and manufacturing machines and to identify potential bottleneck operations.[2.1] The parts will be loaded, machined, washed, and then inspected for dimensional accuracy. The goal is to provide just-in-time manufacturing of one shipset of 541 parts each week. All of these parts fit in a 30-cubic-inch envelope. Planned benefits include reducing machining time from 200,000 hours to 70,000 hours, 32 fewer machines, in only 31,000 square feet of floor space. An estimate of saving \$20,000,000 over the life of the contract was made which is for 100 sets of parts for the B-1 bomber.

2.2.2 BENDIX AIRCRAFT BRAKE AND STRUT DIVISION

The Aircraft Brake and Strut Division (ABSD) of Bendix Corporation recently installed an FMS to machine 22 different piston housings. These piston housings are used in the brake assemblies on a variety of commercial and military aircraft. The model mix for these brake assemblies represents a combination of current production aircraft and replacement parts for maintenance of older airplanes resulting in low volume production of many parts. The FMS was installed and phased into operation without an inspection station in order to simplify and expedite bringing the system on-line. Now that the operating characteristics of the FMS are stabilized, a CMM will be integrated into the system. The CMM was planned as part of the system and provisions for material handling and floor space were included in the original plan.

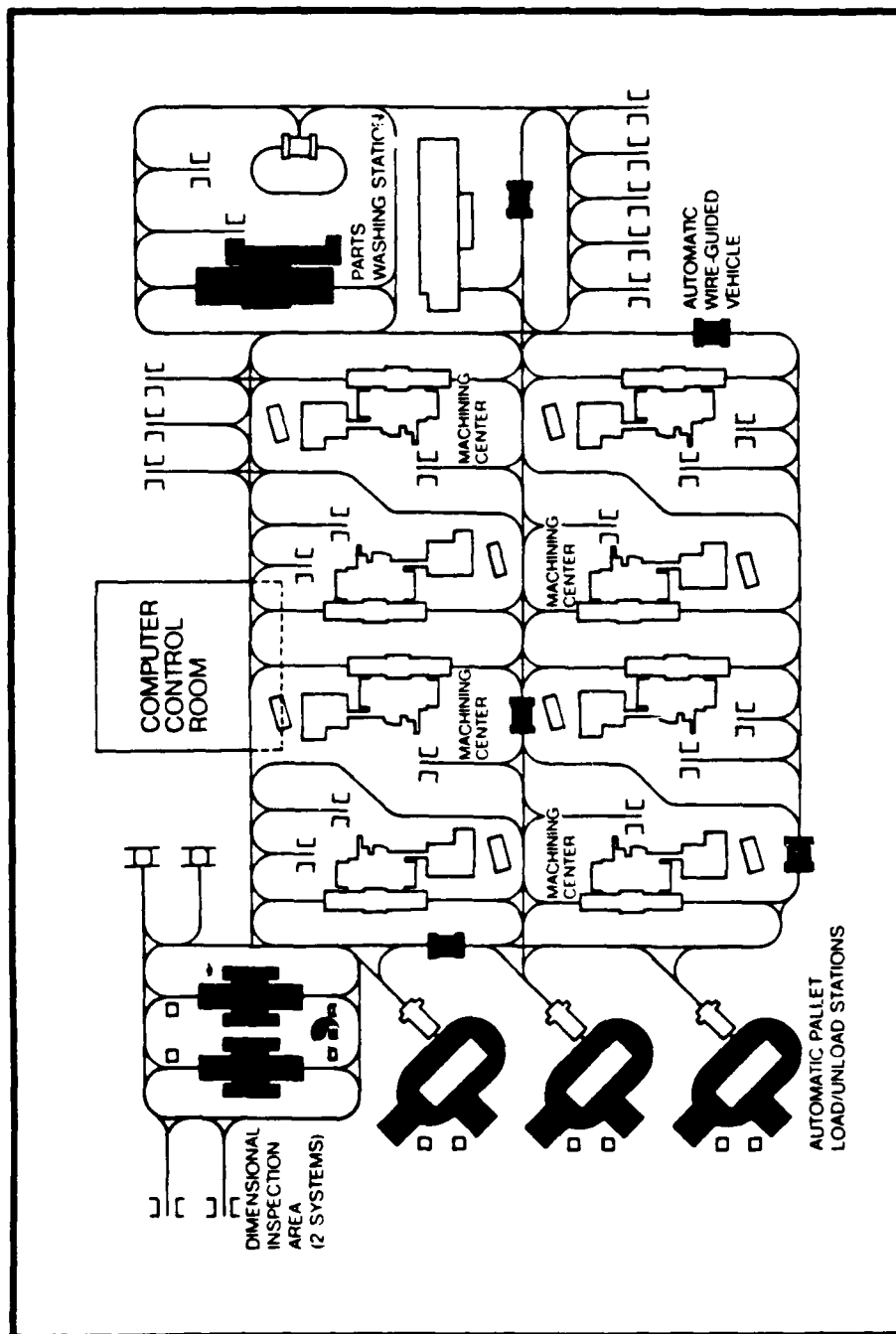


FIGURE 2.1 LTV FMS

The specifications for the CMM are for a horizontal arm machine to facilitate moving the palletized housing in and out of the CMM and to provide a better fit to the shop floor environment. The CMM will have an eight-station probe changer to accommodate the different sizes and type of probes needed for the model mix. All probes will be contact type probes. Internal threads will be the only machined features on the housings that cannot be inspected on the CMM at this time.

The delayed implementation plan for the CMM had one minor negative side-effect that affected the selection of the CMM vendor. The primary choice for CMM vendor would not accept responsibility for the integration of the communications software interface to the FMS because of retrofitting the interface to the existing FMS.

2.2.3 LUCAS MACHINE DIVISION OF LITTON INDUSTRIES

Lucas machine has combined two of their boring mills, an automatic toolchanger, an AWGV, a tool preset area, and a Mauser CMM into an FMS. The FMS is controlled by a VAX 11/750 series computer serving as host to General Electric Mark Century 2000 CNC controllers at each machine. The software system has a hierarchal structure that simplifies expansion, modification, or enhancements at each level of control. The computer also sequences the parts through the required operations including fixturing, machining, refixturing, and inspection.

The software system also includes a tool management system that manages the large tool inventory, calculates and tracks tool life, and directs the movement of tools between storage positions and machining operations. The CNC controllers at each machine monitors the spindle drives to detect increases in horsepower that indicate tool wear and calls for tool change when the tool becomes dull.

Potential problem areas such as coolant levels, motor temperatures, and violations of safety zones on the machine are also monitored. Diagnostic messages for these and other problems provide early warning and trouble-shooting assistance to help increase system utilization.

Lucas reports average productivity increase of 300 per cent over their previous conventional machining operations and consistently higher quality levels.

2.2.4 FMC

FMC Corporation's Ordnance Division manufactures the Bradley Fighting Vehicle (BFV) for the U.S. Army. The BFV is a new vehicle that is more complex and has twice as many parts as its predecessor. The increased part mix combined with low initial production rates resulted in a manufacturing plan that was operationally and economically ineffective even on standalone conventional and N/C machine tools. FMC developed an initial conceptual design that went through several revisions because of changing project requirements and internal changes in manufacturing plans. The initial concept and the several revisions were simulated and the configuration and specifications for the FMS evolved from the results of the simulation.[2.2]

The installed configuration (Figure 2.2) consists of four horizontal machining centers connected by an Automated Wire Guided Vehicle system. There is a load/unload station, wash station, off-line workstation, Coordinate Measuring Machine, and an AWGV service area. An FMS computer provides traffic coordination, work order entry, staging, simulation, scheduling, and data distribution.

The CMM is a gantry type unit that provides for delivery and discharge of palletized and fixtured workpieces by the AWGV. The parts will be inspected on a sampling basis under FMS computer control. A local computer will control the CMM. The CMM computer will have two major functions. First it will receive data from the FMS computer for the parts that are delivered to the CMM

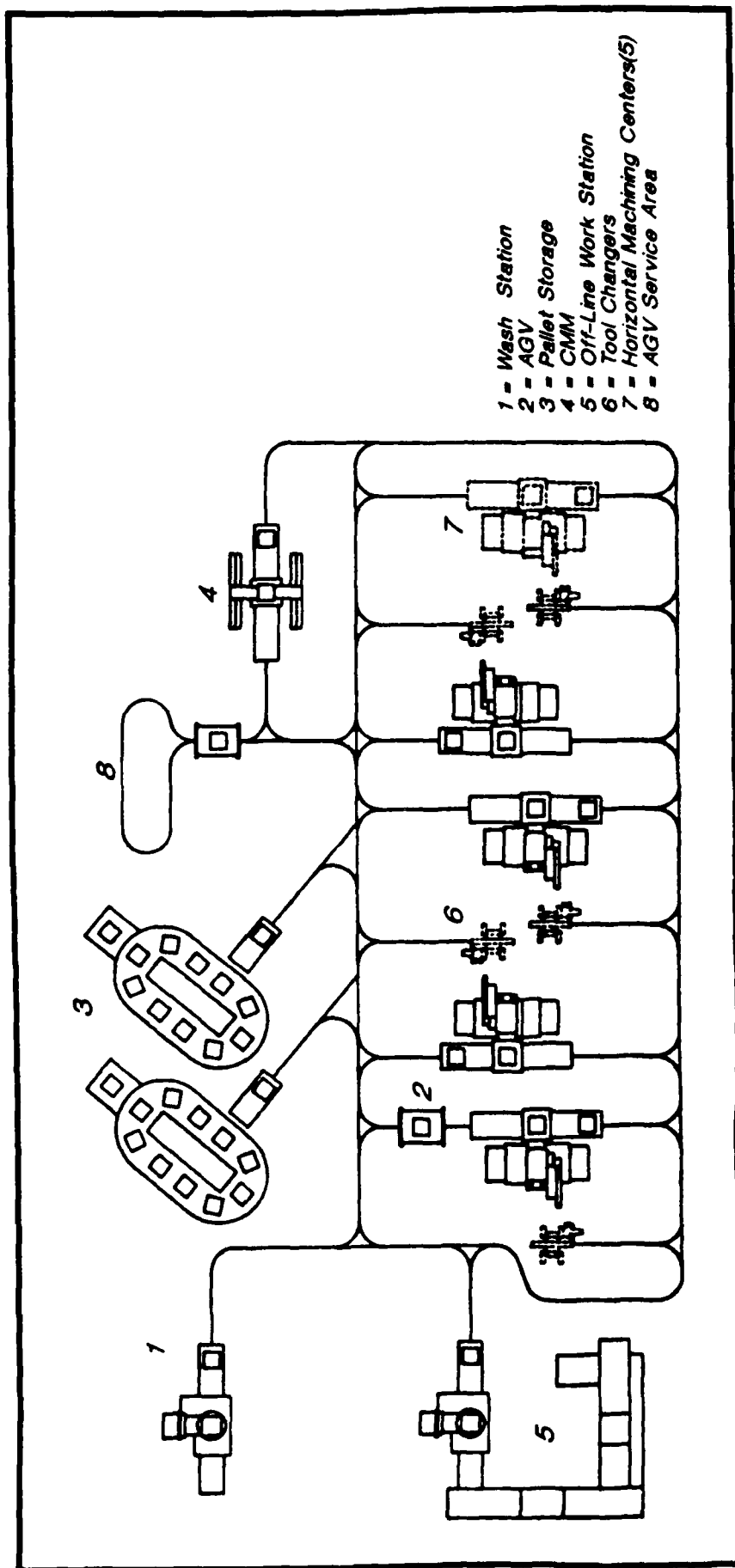


FIGURE 2.2 FMC FMS

and then report the inspection results back to the FMS computer. Secondly, it will provide local control of the CMM for inspection machine functions such as inspection programming, part program storage, and direct computer control of the inspection machine.

2.2.5 TEXAS INSTRUMENTS

The Texas Instruments plant in Carrollton, Texas, has installed an FMS to machine steel and aluminum castings for the HARM missile system for the Navy. The system is designed to machine 40 to 50 different parts. Aluminum castings up to 24 inches long comprise 80 per cent of the part mix. The remaining 20 per cent of the part mix are steel alloy castings. [2.3]

The FMS is made up of six Nigata horizontal machining centers, a robotic deburring station using two GMF - S110R six-axis robots, a Sheffield CMM, and a AWGV material handling system to link the workstations together.

A second FMS consisting of four White - Sundstrand horizontal machining centers, a six axis GMF - S110R deburring robot, and a Zeiss CMM for inspection. Material handling within this FMS is accomplished by a track-mounted Cincinnati Milacron six-axis robot which moves parts through the cell. Nine different missile parts are machined by this FMS.

Production volume for both systems will increase from 30 sets per month in 1986 to 110 sets per month in 1987.

An artificial intelligence system developed by Texas Instruments will be used to supervise and control the first FMS described above. The artificial intelligence system will provide real time machine tool monitoring, machine tool control, and integration to the factorywide automated material handling system.

2.3 NON-FMS APPLICATIONS

2.3.1 BOEING AEROSPACE

Boeing Aerospace has built a flexible inspection system (FIS) for high volume production of parts for the Air Launched Cruise Missile (ACLM) program. This system is unique in that it is a computer-automated, multistation dimensional inspection system with all the features of an automated manufacturing system except that it does not have any fabricating or machining equipment as part of the system.[2.4] The system consists of one Cordax (Sheffield) horizontal arm and one Cordax vertical arm CMM. They are supported by an automated material handling system, a robot based ultrasonic thickness gage, and a computer system for control and coordination of parts flow, acquisition of inspection data, data analysis, and report generation. The FIS is designed to randomly accept ACLM airframe parts from several manufacturing areas and inspect these parts before they are staged for the next manufacturing operation. Depending upon production volumes, cycle times, and inspection requirements, an FIS can theoretically serve multiple manufacturing systems. Figure 2.3 depicts the Boeing FIS configuration.

2.3.2 GENERAL ELECTRIC - EVENDALE

General Electric's Aircraft Business Group in Evendale, Ohio, is using a combination of automated inspection techniques to perform in-process inspection of turbine engine airfoil blades and vanes.[2.5] They are using an X-ray Inspection Module, an Automated Fluorescent Part Penetrant Module, a Infrared Inspection Module, and a Coordinate Measuring Machine. These techniques are being used at specific points in the manufacturing process to scan turbine blades for internal casting flaws, manufacturing errors such as misdrilled cooling passages, dimensional integrity, and final inspection for critical characteristics such as blocked cooling passages.

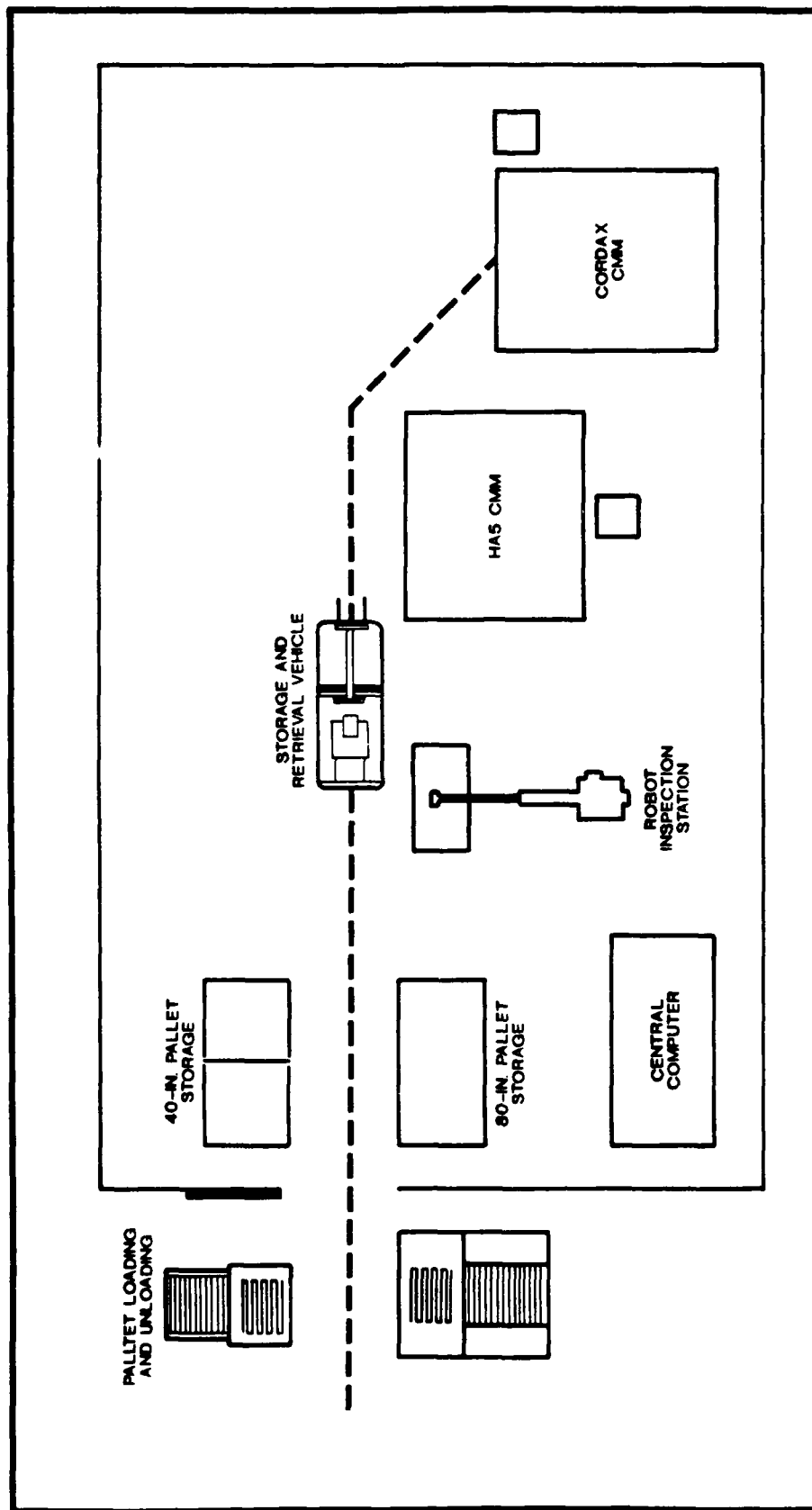


FIGURE 2.3 BOEING FIS

Another element of the inspection system is a computer system that digitizes the inspection plan and links the other modules together. The inspection system computer also provides the interface between the centralized database in a mainframe computer and the minicomputers that provide local control of the inspection modules. The total inspection system provides the capability to perform 100 per cent inspection of the parts on a cost effective basis. Because the system combines image processing and flaw detection with automatic operation, a larger set of inspection data is available for more parts in a timely and efficient manner.

2.3.3 FORD WIXOM CANADA

The Ford Assembly Plant in Wixom, Canada uses a pair of coordinated, moving column, horizontal arm CMMs to inspect automobile bodies.[2.6] This inspection station automatically loads, inspects, and unloads a variety of models. Data gathered in the inspection station is used to improve the fit of sheet metal body panels in the assembly process. Statistical analysis of the data is used to derive and correct process trends.

3.0 POST PROCESS INSPECTION

Post-process inspection uses a variety of sensing technologies to inspect the workpiece while it is still on the machine tool but after the machining process is complete. Most installations install sensors or measuring probes in tool locations in the tool magazine. Other installations use a separate robot arm to select the next sensor or probe in sequence and move it into position after the machining cycle.

This approach adds time to the machining cycle and requires sensors and probes that can fit into the workplace envelope. Miniaturization of vision and laser measurement devices and enhanced signal transmission from fibre optics will improve the application of post process inspection on the machine tool when this approach is necessary because of measurement locations such as internal diameters.

Another disadvantage to doing post process inspection on the machine tool is that machine system errors can go undetected. This deficiency can be compensated for by measuring the finished part on the machine and then repeating the measurement process on the same part in an independent inspection station. The two measurements of the same part are then compared and differences in measured features are recorded. These differences in measurements are fed back to the machine controller and used to adjust the machining process for subsequent parts. This technique is limited to the machining of multiples of the same parts and cannot be used for machining parts in production lots of one.

Post process inspection can use either contact type sensors such as touch-trigger probes and caliper gages or noncontact type sensors such as laser interferometers, scanning laser micrometers, and vision systems. Caliper gages tend to limit flexibility because they are often unique to a part. Maintaining FMS flexibility would require multiple caliper gages and a system for interchanging them in addition to the control programs for manipulating the gages and processing the data.

Initially, machine tool mounted touch trigger probes were used to improve set-up quality and to reduce set-up time. Several problems surfaced when touch trigger probes were first used to perform inspection operations on machine tools starting in about 1977. Major problems included:

- probes could not tolerate the harsh operating conditions
- difficult to transmit reliable signals from the probes to the process controller
- slow operating speeds due to probe waiting for sequential instruction processing by microcomputer controllers
- unique features and software provided by each machine tool builder required a unique probe.

Developments in probe technology in the last seven years have focused on these problem areas. Probes have been hardened to withstand several million operating cycles in harsh environments. Generic transmission protocols simplify the application of probes to a variety of machine tools. Faster microcomputers that use hierarchal control structures and improved software have increased operating speeds for inspection operations. The need for unique probes has been reduced through the use of standardized interfaces by the machine builders.

Touch-trigger probes have been used to measure internal and external dimensions on machined parts. The probe is stored in the tool turret and loaded to the machine tool the same way a cutting tool is loaded. Usually, the program moves the tool to a known datum surface or surfaces to locate the part in the work area. The program moves the probe to the features to be measured, records the measurement value, and compares the measured coordinates to the datum point coordinates to calculate the part dimension. The measured results can be used to adjust the machine controls for a finish cut or to modify tool offsets for error correction on subsequent parts.

Virtually all new turning centers and most machining centers now come equipped with some form of touch trigger probe. FMS installations that have CMMs use the probes primarily for set-up and tool offset calculations. Single

machine operations and FMS installations without CMMs use the probes to do post-process inspection on the machines.

Technology developments in laser and vision sensors have improved their accuracy, reliability, and tolerance for machining operations. These improved sensors enable noncontact type gages to be used to accomplish the same task as the touch-trigger probes. Speed and flexibility are the advantages of using a noncontact gage. The disadvantages are environmental requirements, size, and cost.

4.0 ON-MACHINE GAGING

On-machine gaging uses noncontact type sensors mounted on the machine tool to monitor the part configuration during the machining cycle and controls the machining process to produce the desired part. Several different sensor technologies such as vision systems, laser based optical scanning systems, or acoustic monitoring can be used to control the process. The major difference between post-process inspection and on-machine gaging is that on-machine gaging takes place during the machining cycle. This reduces cycle times and increases the opportunities for closed-loop machine control.

Another advantage of on-machine gaging is that the structural rigidity of the machine tool can be reduced resulting in a lower cost machine. Sensors and software can measure and control the variations in part location within the machine envelope and can compensate for the lack of rigidity by adjusting the process during machining to achieve the desired tolerances. Other advantages of on-machine gaging include low cost, flexibility, and programmability. Major limitations include the adverse impact of hostile environments on measurement results and increases in cycle time.

George Fischer-Bohle markets an optoelectronic measuring system that features non-contact measurement of shape, location, orientation, and runout characteristics of the external contours of shaft-type components. Continuous optical scanning along the Z-axis using semiconductor laser emitters provides measurement data to a processor. Computer analysis of the images' diffraction pattern ensures accurate measurements.[4.1]

A milling center at the Rock Island Arsenal (RIA) uses an optical sensor to measure the position and area of openings being cut into thin-walled cylinders. The system has reduced area variations and positioning deviations by a factor of three, increased machining speeds, and requires one third of the time of a separate CMM inspection. RIA is also using two non-contact sensors to inspect and control the turning of 14-inch diameter shafts on a CNC flat-bed lathe.[4.2]

An example of how on-machine gaging can be used to improve the performance of an FMS operation to gain a competitive advantage can be found at Allen-Bradley. Allen-Bradley is a major supplier of process controllers to the automation industry. One of their other product lines, contactors and relays, was facing stiff competition from foreign companies and was not competitive in worldwide markets. Allen-Bradley developed a competitive strategy that focused on lower production costs through:

- reductions in material, direct labor, and indirect labor costs
- reduced scrap and rework
- increased rates of production
- minimum inventories
- minimized capital investments for product changes

They designed, built, and are operating an automated production facility within their 80-year-old building in Milwaukee, Wisconsin. The new production facility produces 125 product variations at the rate of 514 units per hour. Orders are processed and shipped within two working days of order input to the system. The automated facility has reduced production costs from \$10.19 per unit to \$6.42 per unit.

There are several automated inspection operations in the process. One of these automated inspection operations is similar to FMS inspection operations. A critical magnet grinding operation is controlled by a laser gaging and vision system. This system checks the dimensions and alignment of the magnets and provides feedback to automatically change the grinding set-up to keep the magnets within specifications.

4.1 ON-MACHINE GAGING RESEARCH

The problems associated with on-machine gaging are being investigated by sensor manufacturers, universities, and several research organizations. One of the research organizations that is concentrating on this area is the Industrial Technology Institute.

The Industrial Technology Institute is a not-for-profit corporation organized in 1982 to focus resources on improving America's manufacturing productivity. It is dedicated to research and development of computer integrated manufacturing.

Most of today's on-machine gaging applications are based on contact measurement techniques. These techniques tend to add time to the production cycle when installed on a machine tool. ITI metrology research and development activities are emphasizing non-contact measurement techniques that can be performed during the machining cycle without adding time to the production cycle. There is a trend toward monitoring the machine cycle and providing real-time feedback to the process controller (deterministic metrology). Both measurement techniques require improvements in sensor technology, sensor fusion (integration of multiple sensor inputs), and factory hardened reliable systems.

Research efforts are being directed toward error prediction and correction, in-process gaging, and tool condition monitoring.[4.3] Other categories of machine monitoring that are included in the research activities include:

- workpiece identification
- workpiece set-up
- tool identification
- tool offset measurements
- detection of chip congestion
- machine diagnostics.

5.0 - DETERMINISTIC METROLOGY

Deterministic metrology is a technique of monitoring the parameters of the machine tool and using the real-time data to control the machining process. The concept of deterministic metrology is to concentrate on making a good part by measuring and controlling the process parameters rather than measuring the completed part. Dr. John Simpson, director of the National Bureau of Standards Center for Manufacturing Engineering explains deterministic metrology as "instead of using the product to monitor the process, it is now possible to monitor the process itself, and so control the quality of the product." (1) The technique requires a detailed mathematical model of the machine tool that accurately represents the interactions of the parameters being monitored. A local computer receives data from sensors monitoring the machine's parameters, compares the real-time data to the model, and adjusts the machining process to maintain the specified process parameters.

The need for process monitoring is created by the concept that if a process is established to produce a part as designed, then repeating that process accurately and reliably should produce a good part every time. Several key factors must be present to adequately monitor a process to achieve untended operation.

First, the part design must be well documented in a form that can be communicated to computers controlling the system. Secondly, the normal parameters of the process and any allowable deviations must also be defined in a computer language. Third, the machining, material handling, and inspection systems must be reliable. Finally, the design of the FMS and its components must be thoroughly planned.

The theory of process monitoring and control is well established in several industries such as the refining of petroleum products. If machining processes could be defined, monitored, and controlled with similar confidence levels, the need for physical inspection of machined parts could be eliminated or at least significantly reduced.

A truly flexible machining system will probably always require some form of physical inspection of the parts produced by the system. The number of variables that need to be monitored and controlled in a system that produces one unit of many different parts would make the system too complicated.

Sensing devices used in process monitoring are different from those used for workpiece gaging. Process monitoring devices include:

- force sensors and transducers for tool wear and loads on spindles and shafts
- load sensors for electric motors
- tool presetting systems that automatically transfer tool offset data to the machine controllers
- acoustic emission sensors that detect sound signals from the process
- vibration sensors that detect and transmit vibration data to the controller.

Improvements to these sensing devices increase the accuracy and validity of the detected signals. Miniaturization and environmental hardening of sensor devices coupled with signal transmission improvements provide increased application opportunities.

Future improvements to process monitoring effectiveness will come from the application of artificial intelligence to control systems in addition to continuing improvements in sensors. Artificial intelligence will allow for faster processing of multiple sensor signals and enhanced fault diagnosis of deteriorating parameters.

Deterministic metrology research is being conducted at many institutions. An example of the type of research being conducted is described below.

5.1 AUTOMATED MANUFACTURING RESEARCH FACILITY (AMRF)

The National Bureau of Standards (NBS) has established an Automated Manufacturing Research Facility (AMRF). It is a research facility designed to focus on the measurement and standards needs for automating the small batch and discrete part manufacturing industries. The AMRF is conducting research in many areas relevant to automated manufacturing. Two of these areas, machine tool metrology and machine tool sensor systems, are significant to this review.

The first area, machine tool metrology, is directly related to the deterministic metrology philosophy discussed in the background section of the introduction to this review. Specific efforts include improvement of the point-to-point positioning accuracy of computer controlled machining centers through the use of on-line computer modeling and process monitoring, and development of quantitative techniques for evaluating and improving the performance of coordinate measuring machines. Several approaches to enhancing machining accuracy are utilized. These include:

- static positioning errors are compensated for by feeding corrections from calibration data into the servo loop of the machining center
- thermal errors are adjusted using data from an array of thermal sensors to provide quasi-real time position correction
- dynamic errors from tool wear, tool chatter, spindle run-out, and machine vibrations are sensed and corrected

Efforts to evaluate and improve CMM performance have focused on developing error modeling software and supporting the development of standard acceptance tests for CMMs.

The second research area, machine tool sensor systems, is important to both deterministic metrology and part inspection or verification. Sensor systems provide the data that the control programs use to monitor and adjust the machining process. Two research focus areas at the AMRF are sensors for incipient tool breakage and sensors for testing and evaluating machine spindle errors.

The results of these research projects are summarized below:

- software error correction of machine dimensional errors improved machine accuracy by a factor of 10
- a machining center with software error correction improved the positioning accuracy of hole location by a factor of 5
- thermal error correction improved the start-up accuracy of a turning center by a factor of 20
- adaptive control of a drilling operation using tool breakage sensors enabled 500,000 holes, 1 mm in diameter in 6 mm plates, to be drilled without drill failures

6.0 CONTROL SYSTEMS

The introduction to this review identified untended operation as a major benefit of flexible machining systems. Reduced manning and expanded capacity with reduced operating expenses are the benefits provided by untended operation. Control systems are essential to being able to establish an untended operation. However, the goals of the FMS design process and the attitudes and support of management play a greater role in determining the effectiveness of an FMS installation.

A recent study by Ramchandran Jaikumar, an associate professor at the Harvard Business School, identified 18 Japanese manufacturing companies that are taking advantage of untended operation of their FMSs. In contrast, there is only one company in the United States that reports an untended operation, and that is Mazak, a Japanese machine tool manufacturer. FMSs installed in Japan since 1982, have achieved untended operation and system uptime of 90 per cent to 99 per cent over three shift operation. Average utilization of U.S. FMSs was 52 per cent over two shifts. The Japanese systems also tended to be more flexible in producing a greater variety of parts on the same machining system.

American and Japanese manufacturers have access to essentially the same hardware and software technology. The difference in results is the design objective. Designing an FMS for untended operation requires the project team to anticipate the possible contingencies and solve problems during the design process instead of during installation and start-up. Also, compromises must be made between reliability and maximum machine output. American companies tend to emphasize high hourly output rates. Japanese manufacturers tend to emphasize reliability and consistency and are willing to tolerate small reductions in output. American companies optimize the output of each system component while Japanese companies optimize the output of the system.

6.1 PROCESS CONTROL

Until just a few years ago, automation of discrete part manufacturing operations concentrated on improving the work place, stand alone machine operations, or material handling functions. Most problems were approached as task automation problems. Manufacturers began taking a broader view of manufacturing automation in about 1984 or 1985. As a result, automated discrete part manufacturing is beginning to look more like a continuous manufacturing process. The flexible machining systems described earlier in Section 2 are examples of this trend. These systems require advanced control concepts such as closed-loop control, redundant operation, distributed control, and process optimization. Figure 6.1 shows the general scheme of a closed-loop control system.

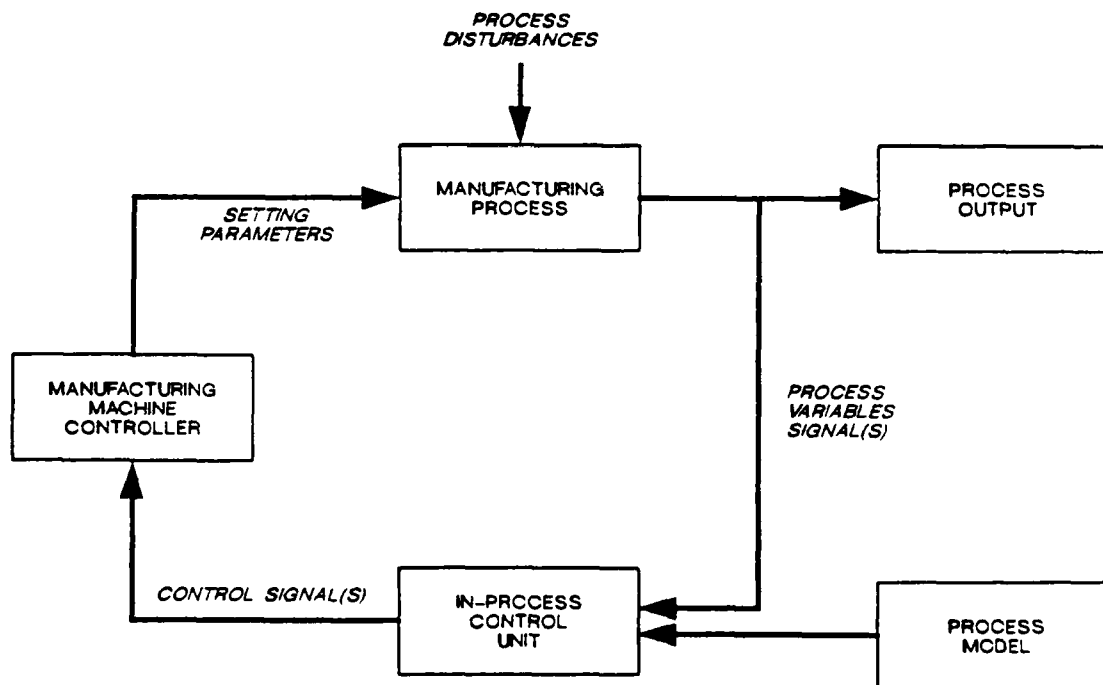


FIGURE 6.1 GENERAL SCHEME OF AN IN-PROCESS CONTROL SYSTEM.

Initial attempts to apply these control concepts to machine cells and flexible machining systems uncovered the difficulties and problems involved with controlling and integrating the many parameters of the systems.

Control and integration problems are typically one of three types. They can be program-to-program problems in which different programs are not able to "talk" to each other. A second type of problem occurs when computers are not able to communicate with each other. The third type of control problem occurs in communications between equipment from different manufacturers. The integration of automated inspection into an FMS provides opportunities for all three types of control problems. These control problems usually impact the ability of an FMS to operate untended or in the transfer of the data defining a part to be machined.

Enhancements to software languages, improvements in sensor technologies, and faster micro-computers are the technologies that have enabled FMS designers to move toward improved process monitoring and control systems. Software enhancements, primarily in the areas of open architecture and standardized interfaces, have made it easier to integrate the many components available to system designers. Components with the best characteristics for a specific application can be used for that application because of the ease of integration with other system components. Improved sensor technologies have increased the variety of features that can be inspected, improved the accuracy of the measurements, and permit near real time measurement in the machining environment.

Hierarchical control systems being developed by vendors, universities, and the AMRF attempt to resolve the program to program type of problem. The various interface standards that are being developed assist the development of the hierarchical control systems as well as problem types two and three. Typically, these control systems recognize that there are different levels of information and control required for different parts of a manufacturing process. The base level is the sensor level which needs to recognize a signal from a sensor, combine it with signals from other sensors if necessary, and pass the processed signal to the next level which is cell control. Cell

control manages the hardware at its level and passes the necessary data to the area manager which controls several cells. The next level in the hierarchy is plant level, followed by a company level.

The interface standards define the number of levels, the functions of each level, signal specifications, timing, and reporting requirements. Standardization is helping to reduce the impact of the three types of problems discussed above. Increased ability of system components to "communicate" with each other provides system designers with more flexibility in selecting the hardware best suited to accomplishing the task at hand.

6.2 PART DEFINITION

One of the problems in the evolution of computer-based machinery and control devices has been the inability of equipment from different vendors to talk to each other. This problem has two forms, The "how do they talk to each other" and the "what do they say." The former is a control problem which is being addressed by the development of common standards and protocols such as MAP. The second form of the problem relates to the type of information to be shared and the format used to transmit the information between devices.

The form of information sharing has been critical to the development of automated inspection systems. The languages and protocols of the many CAD systems were typically incompatible with the languages and protocols of inspection devices such as CMMs. Initial solutions to these types of problems led to the development of unique interface programs for unique pairs of CAD systems and CMMs, an expensive and inflexible solution.

In 1982, a group from Computer Aided Manufacturing - International (CAM-I) working on quality assurance problems met to discuss the feasibility of developing a standard dimensional measuring interface specification (DMIS). DMIS 1.0 was released and demonstrated in 1986. It supports communication between CAD systems and CMMs. The specification is designed to support a broad range of equipment including CMMs, laser measurement systems, optical

comparators, video inspection systems, and robotic measuring devices. DMIS 2.0 is being developed to provide for multiple sensor inputs and other enhancements. It was delivered in October, 1987 by the developing CAM-I member, Pratt and Whitney. Final review of the new enhancements is underway and release of the final specification is scheduled for the first quarter of 1988.

6.3 SENSORS

Human operators use their eyes, fingers, and ears to acquire data about a process or product. The operator processes these data based on his experience and training to determine the condition or status of an operation or the quality of the part he is producing. Sensors are the eyes, fingers, and ears of the process control computer.

Sensors can be categorized according to either the type output they produce or the type of variable they measure.[6.2] The output categories are digital or analog, which needs to be considered in the detail design of a system. The types of variables measured by sensors are the same types of process variables that a control system needs to monitor and control in order to manage the machining process. The primary variable types are mechanical, fluidic, thermal, optical, and acoustic. Each of these primary variables can be categorized into several sub-sets. For example, mechanical variables can include motion, position, proximity, force, or torque. Some of these secondary categories can be measured or sensed by more than one primary category. Optical or acoustic primary types of sensors can also be used to sense proximity. An excellent description of the categories of sensors and their types of applications is contained in [Chryssolouris and Patel].[6.2]

The important point to be considered in this discussion is that recent developments in sensor technologies are producing sensors that are more accurate, sensitive, and hardened for the machining environment. Some of the major developments have been in fibre optic sensors, acoustic sensors, and vision systems.

6.4 ARTIFICIAL INTELLIGENCE

The development and application of common standards and protocols such as MAP and DMIS are improving the integration of FMS components including automated inspection. Future improvements will come from the development and application of artificial intelligence in the FMS control systems. Artificial intelligence will increase the flexibility of the FMSs including automated inspection by reducing the need to program processes for individual parts. Artificial intelligence will allow task-performing devices to intelligently interact with other devices and their surroundings. Such a device would be given a high-level command that would enable the device to gather the required resources, figure out the sequence of elementary tasks, and sense and correct the operating condition as necessary. A programmer would not have to imagine every contingency and provide checks and branch programs for each. We will gradually move from writing task-specific programs for machine tools or robots to general operating programs that would enable the device to handle conditions as they develop during the course of normal operation.[6.1]

Inspection of the part and the process making the part will become a continuous real-time task that will prevent defects from being machined rather than detecting defective parts.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Four key conclusions can be made based on the information available about automated inspection in flexible machining systems.

1. There are very few FMS installations that have automated inspection fully integrated into the system.
2. A major factor is the reluctance of management to invest large amounts of capital because of concerns about the length of the payback period.
3. Many vendors, user groups, and research institutions are actively involved in research and development in all aspects of automated inspection.
4. The trend in FMS automated inspection is toward controlling the process through in-process gaging and deterministic metrology.

The above conclusions are discussed in more detail below.

7.1.1 FEW FMS AUTOMATED INSPECTION INSTALLATIONS

Flexible machining systems are not a new concept, yet there are only 150 to 200 FMS installations worldwide. Only 30 to 50 of these systems are in the United States. Because the concept of integrating automated inspection into an FMS is relatively new, there are very few examples of working installations.

The majority of installations are in aerospace and defense manufacturing companies. The impetus for these systems comes from the need to efficiently machine very low production volumes of high quality, high cost components in coordination with critical production schedules for other components and assemblies.

Other significant installations of automated inspection are being made in some high volume industries such as automobiles. The key issues in these installations is the just-in-time production of quality parts. Most of these installations are in fabrication, assembly, and painting operations. The importance of these installations is that they demonstrate the application of automated inspection technology that could be applied to flexible machining systems.

The absence of standardized interfaces in areas of part definition and communications between hardware and software has slowed the development of FMSs. Since automated inspection was one more function that needed to be integrated, but was not absolutely necessary for a functioning FMS, it has often been excluded from the FMS functions.

7.1.2 MANAGEMENT ATTITUDE

Based upon the comparison of FMSs that run untended in Japan compared to the United States, it appears that Japanese manufacturers are significantly ahead in the application of automated inspection in FMSs. The hardware is comparable while US software is generally considered to be more efficient and integrated than Japanese software. The difference in successful applications is in the attitudes and commitment of management.

American managers are preoccupied with applying only technologies that do not decrease short-term profits. As a result, many applications are delayed while waiting for a better "mouse trap". Other applications don't make it beyond the concept stage because they are unable to meet the financial goals set by management. In contrast, Japanese managers are committed to using available technology to gain a competitive advantage and market share over the long term.

7.1.3 RESEARCH AND DEVELOPMENT

Research on automated inspection for FMSs is being conducted by system developers; vendors of equipment, tooling, and software; universities; and government agencies. Many of the research projects are joint efforts; for example:

- National Science Foundation provides funds to universities and private companies to research selected aspects of manufacturing automation
- FMC and the Charles Stark Draper Laboratories worked together to develop the data base and computer simulation programs used to design the FMC FMS for the Bradley Fighting Vehicle.

These research programs are directed at automating flexible machining systems in general but also address the communications and control software necessary to integrate inspection into an FMS. Vendor efforts tend to be proprietary for marketing purposes, but joint development projects are common, especially in the software interfaces.

7.1.4 DEVELOPING TRENDS

The trend in integrating automated inspection into flexible machining systems is toward establishing and controlling the process and away from physical inspection of the part. As the technologies for in-process gaging and deterministic metrology are developed by the research programs and proven in the factories, defect prevention will become the accepted inspection methodology. The best approach is to define the process required, do the process right once to identify the critical parameters of the process, and keep doing it right by monitoring the process parameters.

7.2 RECOMMENDATIONS

Developments in inspection technologies, sensors, systems control software, and communications software are facilitating the integration of automated inspection into flexible machining systems. These developments are

also improving the practicality and economics of FMSs. The range of inspection methodology alternatives available to designers and planners of flexible manufacturing systems is also increasing. Because of the many alternatives and variables involved in integrating automated inspection into an FMS, it is not realistic to make specific recommendations. Each potential application must be analyzed to determine the configuration that will optimize the manufacturing system and not just the inspection operation. Analysis of an opportunity to integrate automated inspection into an FMS should include the following steps:

- Design the inspection system as an integral part of FMS design
- Select parts or families of parts that increase system flexibility
- Determine the features or characteristics of parts that need to be monitored and verified
- Identify the part inspection methodology and process control techniques that enable inspection to occur as early and as continuously as possible in the production cycle
- Establish a review process for comparing the factors that are critical to achieving the goals and objectives of the FMS and inspection systems to the advantages and disadvantages of inspection methodologies shown in Table I-1
- Aim for defect prevention rather than detection.

Integration of automated inspection methods and equipment that are appropriate for the product and the process does not add to the life-cycle costs of a flexible machining system. The resulting improvements in productivity and quality and the reductions in inventory, scrap, and rework costs all improve the profitability of the system.

The examples of automated inspection in flexible machining systems previously cited in this review demonstrate that the technology is working. Companies are getting benefits from integrating automated inspection into their FMSs. Why wait for developments that may only add ten to twenty per cent to the benefits that are already available? Managers at all levels need to aggressively pursue opportunities to use this technology to reduce product costs and to improve productivity, quality, and market share.

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AUTOMATED INSPECTION FOR FLEXIBLE MACHINING SYSTEMS

Date: May 1988

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